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Chemical Warfare Laboratories

Technical Report

CWLR 2340

Studies in Wound Ballistics: Temporary Cavities and Permanent Tracts Produced by High-Velocity Projectiles in Gelatin

by

Max Krauss

John F. Miller

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STUDIES IN WOUND BALLISTICS: TEMPORARY CAVITIES AND PERMANENT TRACTS PRODUCED BY HIGH-VELOCITY PROJECTILES IN GELATIN

by

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U. S. ARMY
Chemical Corps Research and Development Command
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Army Chemical Center, Maryland

FOREWORD

This study was authorized under Project 4C99-02-002, Wound Ballistics (U). The work was started in January 1956 and completed in June 1956. The report was submitted for publication in July 1959.

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In these experiments, caliber .30 and caliber .22 bullets, caliber .30 fragment simulators, and 1/4-inch steel spheres were fired into cylinders of 20% gelatin, some of which were confined in rigid plasticized fiber-glass casings. The data derived lead to the following conclusions:

1. A useful measure of the cross section of the permanent missile tract in 20% gelatin is afforded by the length of the longest radial split as measured on the surface of the gelatin cylinder.

2. A close approximation to the circumference of a temporary cavity in 20% gelatin is obtained by multiplying by 2 the sum of the length of all the radial splits extending from the missile path at a given level.

3. The formation of a temporary cavity is almost completely suppressed in 20% gelatin confined in a rigid casing. Radial splitting of the gelatin around the permanent missile path is also greatly reduced in confined gelatin cylinders.

4. Energy absorption in 20% gelatin shot with high-velocity missiles is independent of temporary-cavity formation, as shown by experiments with confined and unconfined cylinders.

5. Momentum transfer in 20% gelatin is also independent of temporary-cavity formation.

6. More than 99% of the total energy absorbed by 20% gelatin from a nonperforating, high-velocity missile is available for temporary-cavity formation. If the formation of a temporary cavity is suppressed, this energy presumably is dissipated as heat.

CONTENTS

STUDIES IN WOUND BALLISTICS: TEMPORARY CAVITIES AND PERMANENT TRACTS PRODUCED BY HIGH-VELOCITY PROJECTILES IN GELATIN

I. INTRODUCTION

Previous studies of wounds produced in excised goat muscles and livers by stable, high-velocity rifle bullets have shown that the cross-sectional diameter and volume of the temporary and permanent cavities are related in a predictable way.[1] Since most recent quantitative work on temporary cavities has been done using 20% gelatin to simulate animal soft tissues,[2] it seemed desirable for comparative purposes to obtain data pertaining to the relation between temporary cavities and the associated permanent tracts produced by high-velocity projectiles in gelatin. Additionally, it has been possible to obtain new information about the temporary cavity from experiments that could be readily performed with gelatin models, but that could be done only with difficulty, if at all, with soft tissue masses.

II. MATERIALS AND METHODS.

Cylinders of 20% gelatin, 12.5 cm in diameter and either 12.5 cm or 20.3 cm long, were used. For experiments in which the cylinders were rigidly confined, the gelatin was poured into open-end cylindrical casings of 1/4-inch-thick plasticized fiber glass of appropriate length, with an inside diameter of 12.5 cm. In all the experiments, the gelatin cylinders were kept at 10°C for at least 24 hours prior to shooting to insure uniform consistency of the gelatin.

Missiles used in the experiments included: caliber .30, 168-grain armor-piercing (AP M2) and 152-grain ball (M2) rifle bullets; caliber .22 Hornet, 45-grain, full-patch and soft-nose bullets; caliber .30, 44-grain-fragment simulators; and 1/4-inch-diameter, 16-grain steel spheres (figure 1).

Appropriate rifle barrels, fitted into a universal receiver, were used to fire the different missiles. Velocities ranging from 1000 ft/sec to 3200 ft/sec were achieved by varying the powder load. Methods used in this laboratory for measuring and recording bullet velocities have been described in detail by Grossman.[3] The instrumentation for determining entrance and residual velocities is the same, the only difference being in the position of the velocity screen holders with respect to the target.

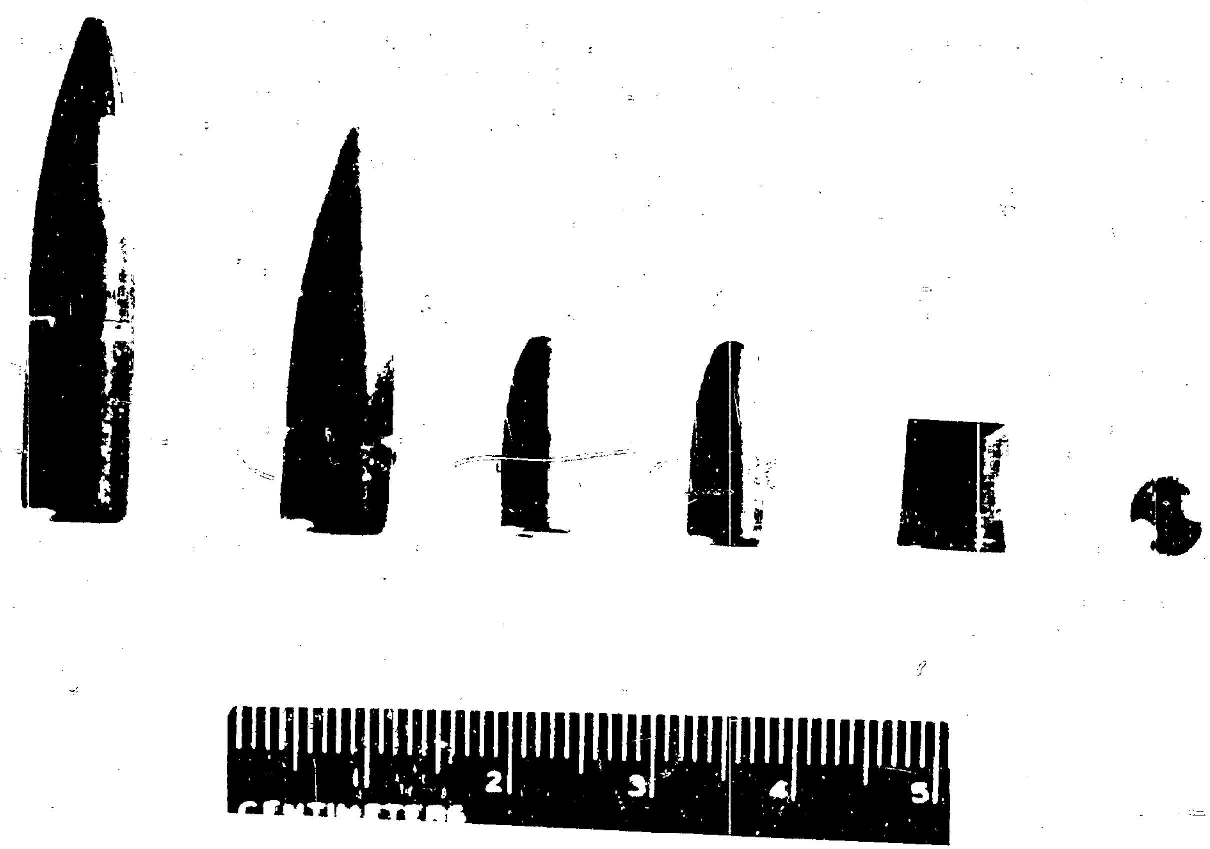

FIGURE 1

PROJECTILES USED IN THE EXPERIMENTS. FROM LEFT TO RIGHT: CALIBER .30 AP M2, CALIBER .30 M2 BALL, CALIBER .22 HORNET SOFT-NOSE, CALIBER .22 HORNET FULL-PATCH, CALIBER .30 FRAGMENT SIMULATOR, 1/4-IN. STEEL SPHERE.

Temporary cavities were visualized by means of microsecond-exposure X-rays produced by a Westinghouse "Micronex" apparatus.[4] Measurements of the diameters of temporary cavities were obtained directly from the film and corrected for the distance between the missile path and the film at the time of exposure. Temperature variations of the gelatin cylinders following equilibration at 10°C for 24 hours were so slight that they could be neglected in calculating the actual temporary-cavity diameters. Measurements of the permanent tracts were made directly on the blocks, which were cut transversely across the missile path at a level at which the temporary-cavity diameter was found to be greatest. Photographs of the cut surfaces of all blocks were taken for a permanent record.

III. RESULTS.

A. Comparison of Cross-Sectional Diameters of Temporary Cavities and Permanent Tracts in Gelatin.

The results obtained with various projectiles fired into 12.5-cm-long gelatin cylinders are summarized in table 1. The data shown in the table pertain to nontumbling projectiles.

Temporary cavities formed in gelatin by similar projectiles under comparable circumstances are remarkably uniform in size and shape. This is reflected in table 1 by the low values for the standard deviation of the diameter of the temporary cavities in the different groups. Representative temporary cavities produced by different missiles are shown in figure 2.

Cross sections of representative permanent tracts are shown in figure 3. The pictures show a variable number of straight cracks extending radially from the missile path. A simple way to obtain a measurement of the cross section of the permanent tract is to measure the length of the longest radial split. This is a more variable quantity than the temporary-cavity diameter, as indicated by the magnitude of the standard deviation shown in table 1. The data show, however, that for the missiles used at the velocities given the longest radial split provides a useful measure of the cross section of the permanent missile tract. In figure 4, temporary-cavity diameter is shown plotted against the corresponding longest radial-split measurement. There is remarkably little scatter in the point distribution, which appears to be essentially linear.

Consideration of the mechanics of the formation of a temporary cavity suggests that twice the sum of the length of all the radial splits at any

TABLE 1

COMPARISON OF TEMPORARY-CAVITY DIAMETERS AND THE LONGEST RADIAL SPLIT IN 20% GELATIN CYLINDERS 12.5 CM LONG, PRODUCED BY VARIOUS MISSILES AT DIFFERENT VELOCITIES: PERCENTAGE OF BULLET KINETIC ENERGY ABSORBED BY THE GELATIN

Missile	Velocity	Mean wt of missile	No. of shots	Temporary cavity		Longest split		Mean KE of bullet at impact	Mean energy absorbed by gelatin*	Per cent of bullet KE absorbed by gelatin
				Mean diam	Std dev	Mean length	Std dev			
	ft/sec	gr		cm		cm		ft-lbs		
Cal .30 AP M2	3200	168	11	8.4	.23	5.4	.39	3730	257	6.9
	2800		9	7.1	.18	4.3	.53	2794	191	6.8
	2400		10	6.0	.19	3.9	.34	2044	137	6.7
	2000		11	5.0	.13	3.0	.30	1449	100	6.9
	1500		10	3.6	.22	1.8	.13	774	59	7.6
	1000		10	2.5	.13	1.3	.16	401	27	9.2
Cal .30 M2 ball	2800	152	11	7.3	.23	4.6	.39	2760	196	7.1
	2000		10	5.0	.13	2.8	.25	1338	116	8.7
	1000		10	2.5	.06	1.4	.13	350	36	10.3
Cal .22 Hornet full-patch	2400	45	11	6.0	.23	3.7	.39	556	87	15.6
	2000		10	4.6	.28	2.6	.34	417	78	18.7
	1500		11	3.0	.16	1.6	.26	236	50	21.2
Cal .30 fragment simulator	2800	44	11	11.5	.43	8.6	.49	784	559	71.3
	2000		10	9.9	.41	6.3	.66	358	257	71.8
	1500		10	7.1	.38	4.3	.31	241	176	73.0
	1000		11	4.8	.20	2.5	.33	86	71	82.6

* All the missiles in this table perforated the cylinders at each velocity.

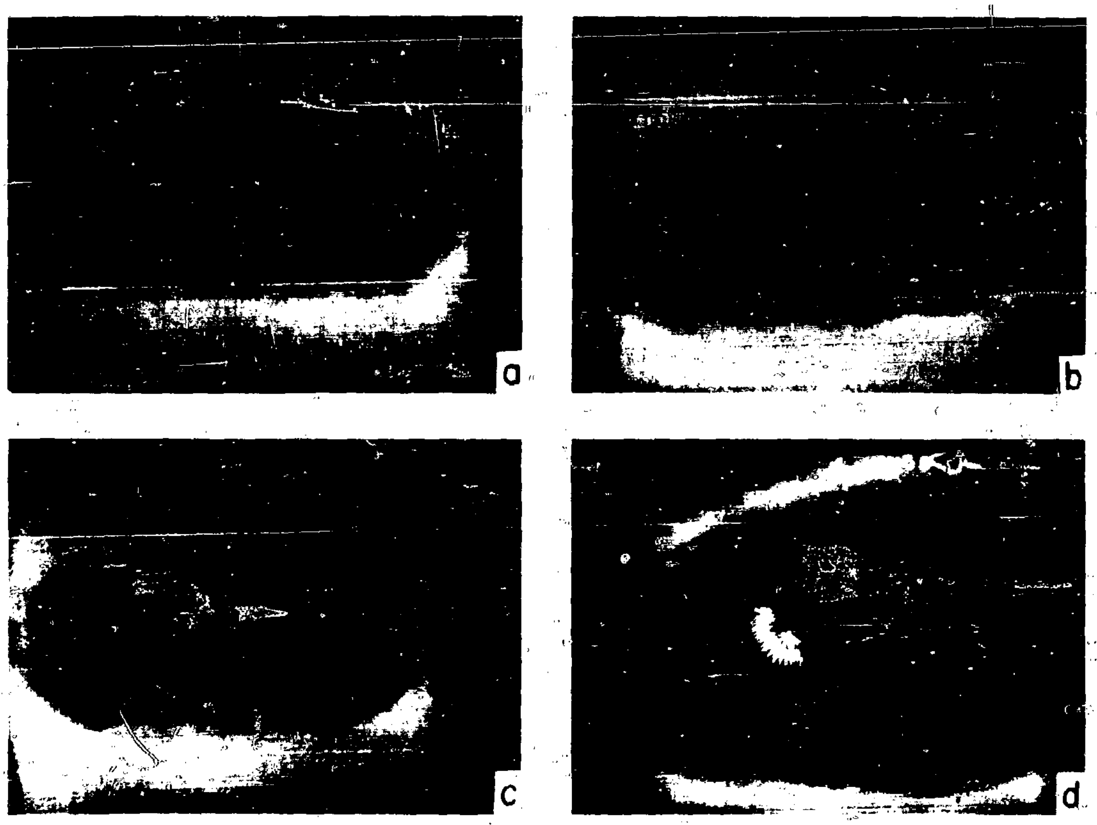

FIGURE 2

MICROSECOND-EXPOSURE X-RAYS OF TEMPORARY CAVITIES PRODUCED IN 20% GELATIN BY VARIOUS MISSILES. EACH EXPOSURE WAS MADE 2000 MICROSECONDS AFTER IMPACT. A. CALIBER .30 AP M2. B. CALIBER .30 M2 BALL. C. CALIBER .22 HORNET FULL-PATCH. D. CALIBER .30 FRAGMENT SIMULATOR.

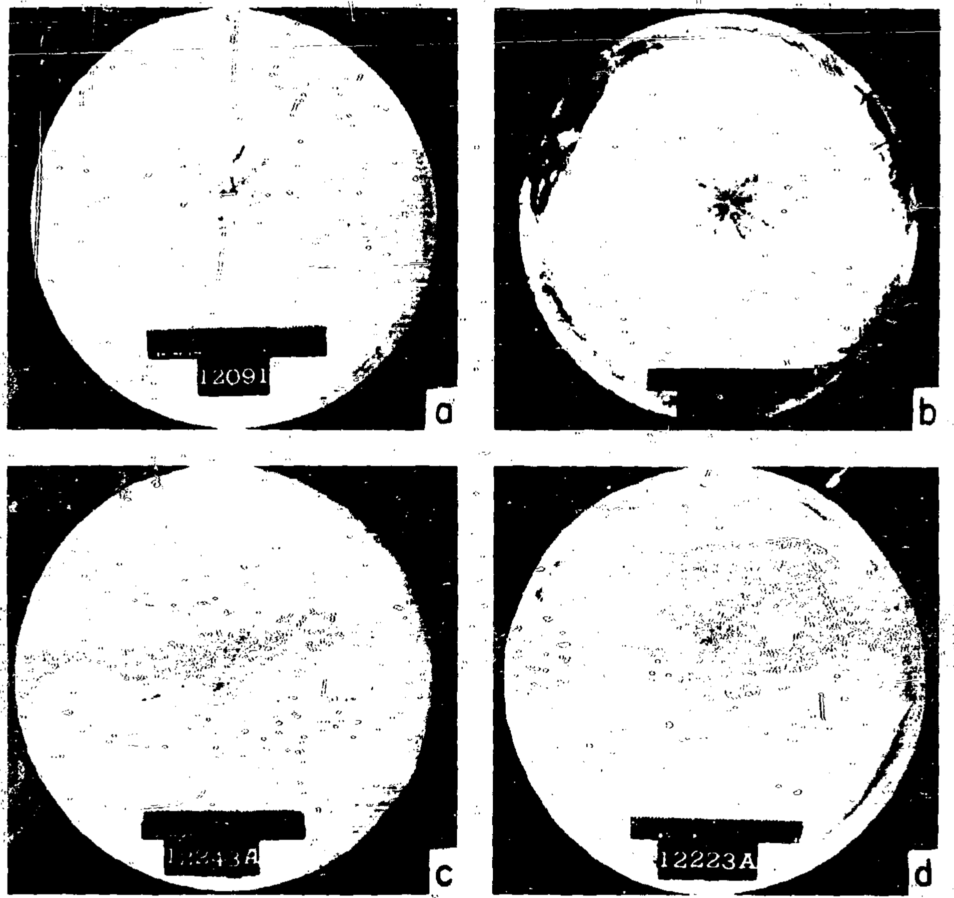

FIGURE 3

CROSS SECTIONS OF PERMANENT TRACTS IN CONFINED 20% GELATIN CYLINDERS. A. CALIBER .30 AP M2. B. CALIBER .30 M2 BALL. C. CALIBER .30 FRAGMENT SIMULATOR. D. CALIBER .22 HORNET FULL-PATCH.

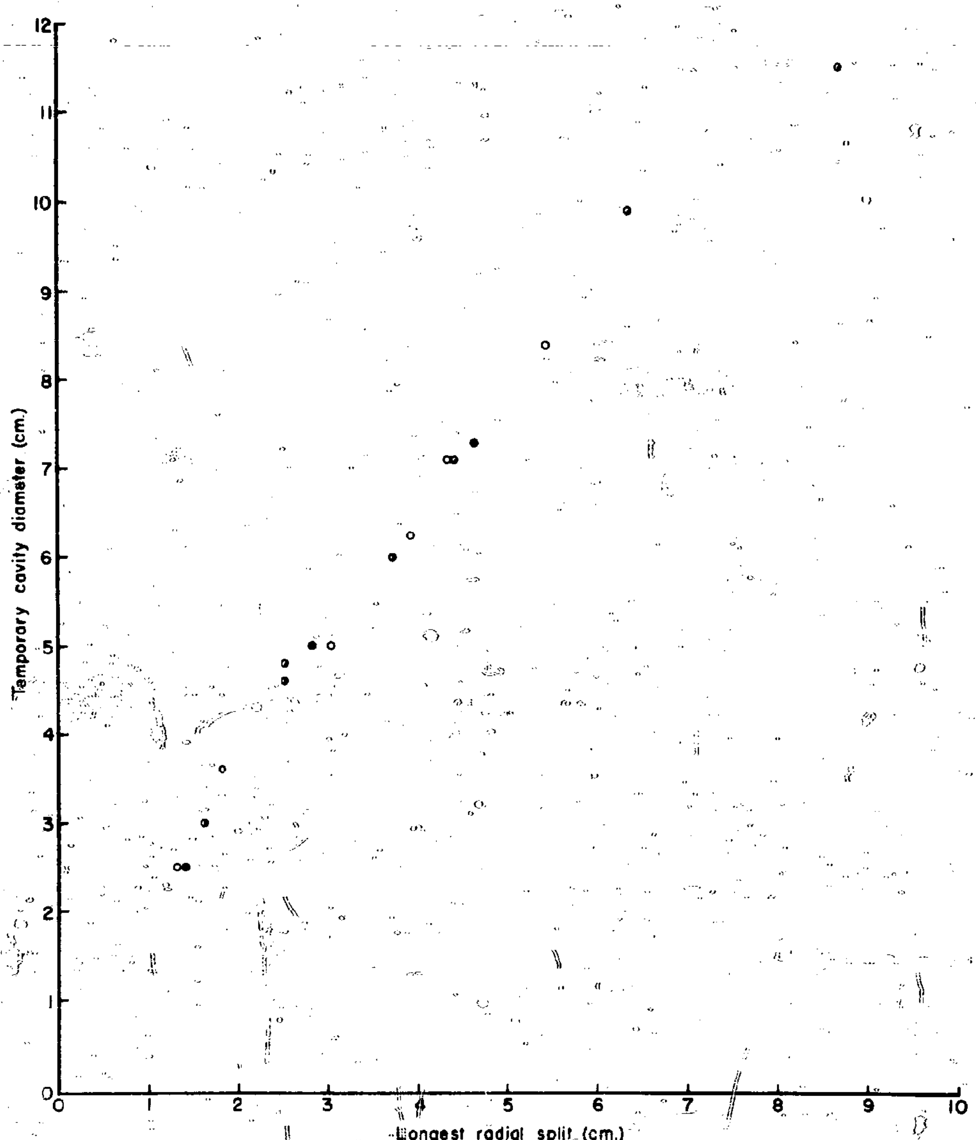

FIGURE 4

TEMPORARY-CAVITY DIAMETER VS.
LONGEST RADIAL SPLIT IN 20% GELATIN.

given level of the missile path in a gelatin cylinder might be expected to approximate the circumference of the temporary cavity at the same level. Accordingly, the length of each radial split extending from the missile path (caliber .30 fragment simulator) in each of a number of gelatin cylinders was measured. The quantity so obtained was multiplied by 2. The resulting value was compared with the computed circumference of the temporary cavity at the same level. As shown in table 2, there is, for the most part, very close agreement in the values obtained. Comparable results were obtained in a few other instances in which measurements were made in cylinders shot with different missiles. It seems safe to assume on the basis of these results that a useful approximation to the cross-sectional dimensions of a temporary cavity produced in 20% gelatin by a high-velocity missile can be achieved by the method described here.

TABLE 2

COMPARISON OF THE SUM OF THE RADIAL SPLITS TIMES 2 AND THE CIRCUMFERENCE OF THE TEMPORARY CAVITY PRODUCED IN 20% GELATIN CYLINDERS BY CALIBER .30, 44-GRAIN-FRAGMENT SIMULATORS AT A VELOCITY OF 1500 FT/SEC

Cylinder	Sum of radial splits times 2	Temporary cavity diam	Temporary cavity circum
		cm	
1	14.8	6.6	20.7
2	33.6	6.0	18.9
3	24.0	6.8	21.4
4	18.6	5.7	17.9
5	19.6	6.5	20.4
6	19.4	6.8	21.4
7	23.8	6.9	21.7
8	25.0	6.5	20.4
9	19.4	6.6	20.7
10	21.6	6.4	20.1
11	18.4	6.4	20.1

It is worthwhile to note at this point the very great differences in the percentage of the initial kinetic energy of the missile absorbed by gelatin cylinders shot with different types of missiles, as shown in the last column of table 1. At comparable velocities, a caliber .30, 44-grain-fragment

simulator gives up from 71% to 83% of its energy, while the AP M2 and M2 ball bullets give up only from 7% to 10%. Interestingly, the caliber .22 Hornet, 45-grain full-patch bullet loses a higher percentage of its energy than does the caliber .30 rifle bullet. Among the factors that influence the amount of energy a particular missile loses upon penetrating a target medium are the shape and area of the presented surface.[5] In the case of a nontumbling bullet this is dependent on the ogive of the bullet as well as its resistance to deformation.

B. Suppression of Temporary-Cavity Formation in Gelatin.

The results presented in the preceding section suggest that factors influencing the expansion of a temporary cavity would have a corresponding effect on the permanent tract. Whether the slope of the linear function is changed is, however, a matter for conjecture at this time.

It has been found possible to suppress almost completely the expansion of the temporary cavity, which would otherwise occur following passage of a high-velocity missile through a medium such as 20% gelatin, by confining the gelatin in a rigid casing. In the present experiments radial expansion was largely prevented by molding the gelatin in cylinders of 1/4-inch-thick plasticized fiber glass (figure 5a). Plasticized fiber glass is highly nondeforming and has an extremely high resistance to shattering. Most of the longitudinal component of the expansion was suppressed by clamping 3/8-inch-thick plates of hardened aluminum alloy to the open ends of the gelatin-filled cylinders. A 1-inch-diameter hole was provided in the center of each end plate, except in the special case to be described in a subsequent section, to allow unimpeded passage of the projectile through the gelatin. A completed 20.3-cm-cylinder assembly is shown in figure 5b.

For control purposes, unencased gelatin cylinders were clamped between end plates with just sufficient pressure to hold the cylinders in place. Control cylinders are henceforth referred to as "unconfined," while the encased cylinders are referred to as "confined."

Suppression of temporary-cavity formation is illustrated in the microsecond-exposure roentgenograms shown in figures 6 and 7. The short cylinders (12.5 cm), shown in figure 6, were shot with caliber .30 AP M2 bullets at a velocity of about 2800 ft/sec. The long cylinders (20.3 cm), shown in figure 7, were shot with caliber .22 Hornet soft-nose bullets at a velocity of about 2400 ft/sec. The Hornet bullets mushroomed and failed to perforate the cylinders. In the case illustrated in figure 6, the roentgenograms were obtained at a time, following bullet impact, at which the

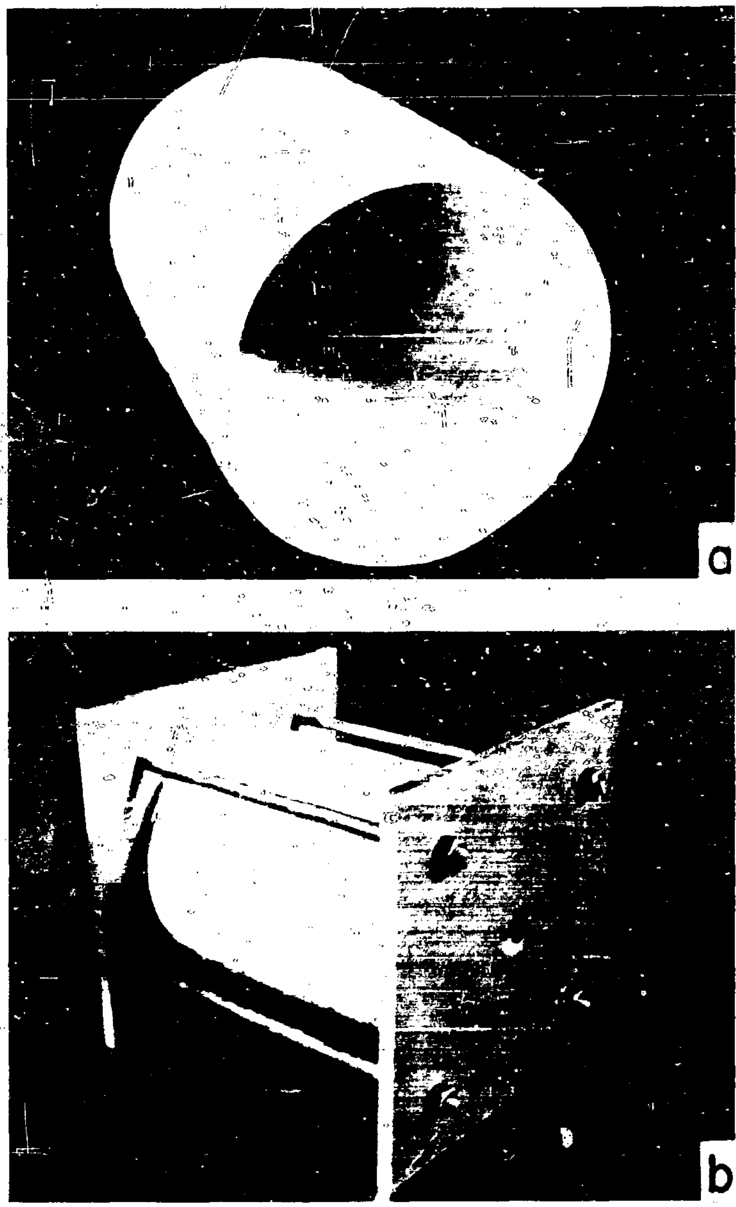

FIGURE 5

A. PLASTICIZED FIBER-GLASS CASING 20.3 CM LONG, 1/4-IN. WALL THICKNESS. B. CASING WITH 3/8-IN. ALUMINUM ALLOY END PLATES

temporary cavity would normally achieve its maximum expansion. It can be seen that there is only a trace of a temporary cavity in the confined cylinder, but in the unconfined one a temporary cavity of normal size appears. In the series of pictures shown in figure 7, the microsecond-exposure roentgenograms were obtained at intervals of 250 microseconds – from 250 to 2500 microseconds following bullet impact. In no case did more than a trace of a temporary cavity appear in the confined cylinders. On the other hand, in the controls and in completely unrestrained cylinders the time constants for the development of temporary cavities of normal size were about the same. The X-rays covered a time span long enough to make certain that cavity formation was not simply displaced in time in the confined cylinders. It should also be noted here that plasticized fiber glass, in the thickness employed in the casings, is sufficiently transparent to X-rays so that the casing does not interfere with visualization of a cavity within the contained gelatin. This is demonstrated by figure 8, which shows a microsecond-exposure roentgenogram of a confined gelatin cylinder in the center of which a 1-inch-diameter hole had been manually excavated.

The permanent tracts in confined gelatin cylinders present a remarkable appearance when viewed from the side or in cross section. Figures 9 and 10 show cylinders that had been shot with caliber .30 AP M2 bullets at 2800 ft/sec and caliber .22 Hornet soft-nose bullets at 2400 ft/sec, respectively. It can be seen in each case that in the confined cylinders there is practically no radial splitting. This is in marked contrast to the unconfined cylinders, in which the permanent tract is characterized by numerous radial splits. It is apparent then, that suppression of the temporary cavity is accompanied by concomitant suppression of radial splitting around the missile path.

C. Energy Absorption in Confined and Unconfined Gelatin Cylinders Shot with High-Velocity Projectiles.

A series of 18 12.5-cm confined gelatin cylinders, and 13 unconfined cylinders of the same length, were shot with caliber .30 AP M2 bullets at a velocity of about 2800 ft/sec. Initial and residual bullet velocities were recorded, and the amount of energy absorbed by the gelatin in each case was calculated according to the equation

$$E_{ab} = \frac{W(V_o^2 - V_r^2)}{2g},$$

where W is weight of the bullet in pounds, V_o and V_r are initial and residual velocities, respectively, in ft/sec, g is the acceleration caused by gravity, and E_{ab} is the energy absorbed in foot pounds.

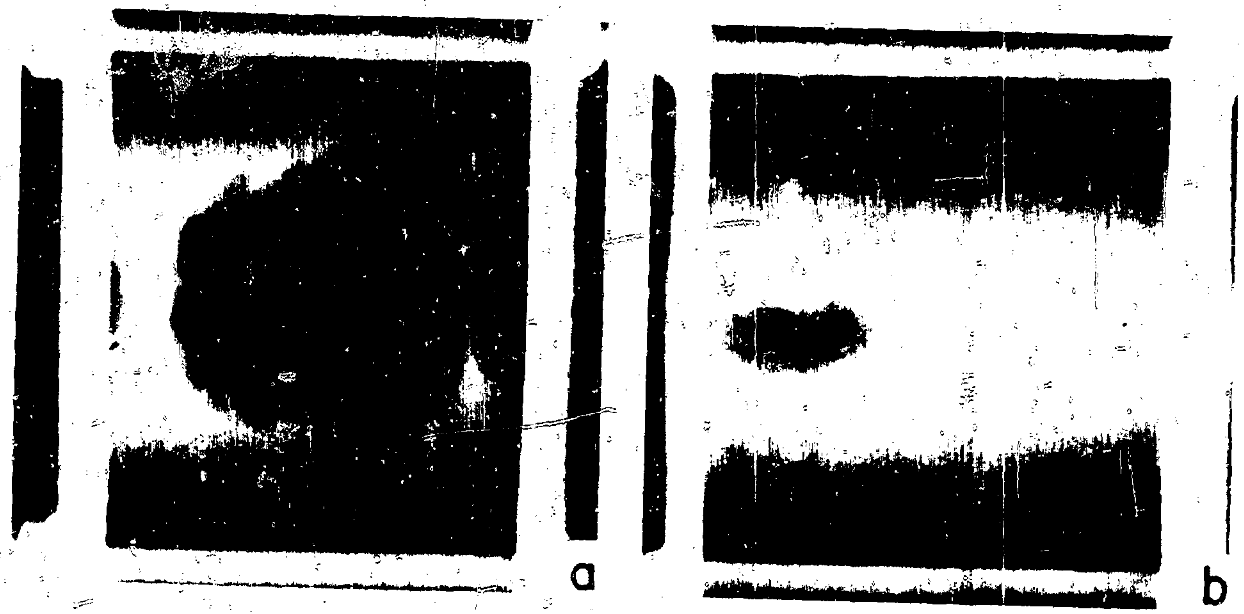

FIGURE 6

MICROSECOND-EXPOSURE X-RAYS OF CONFINED AND UNCONFINED 20% GELATIN CYLINDERS 2000 MICROSECONDS FOLLOWING IMPACT OF CALIBER .30 AP M2 BULLETS.
A. UNCONFINED CYLINDER. B. CONFINED CYLINDER.

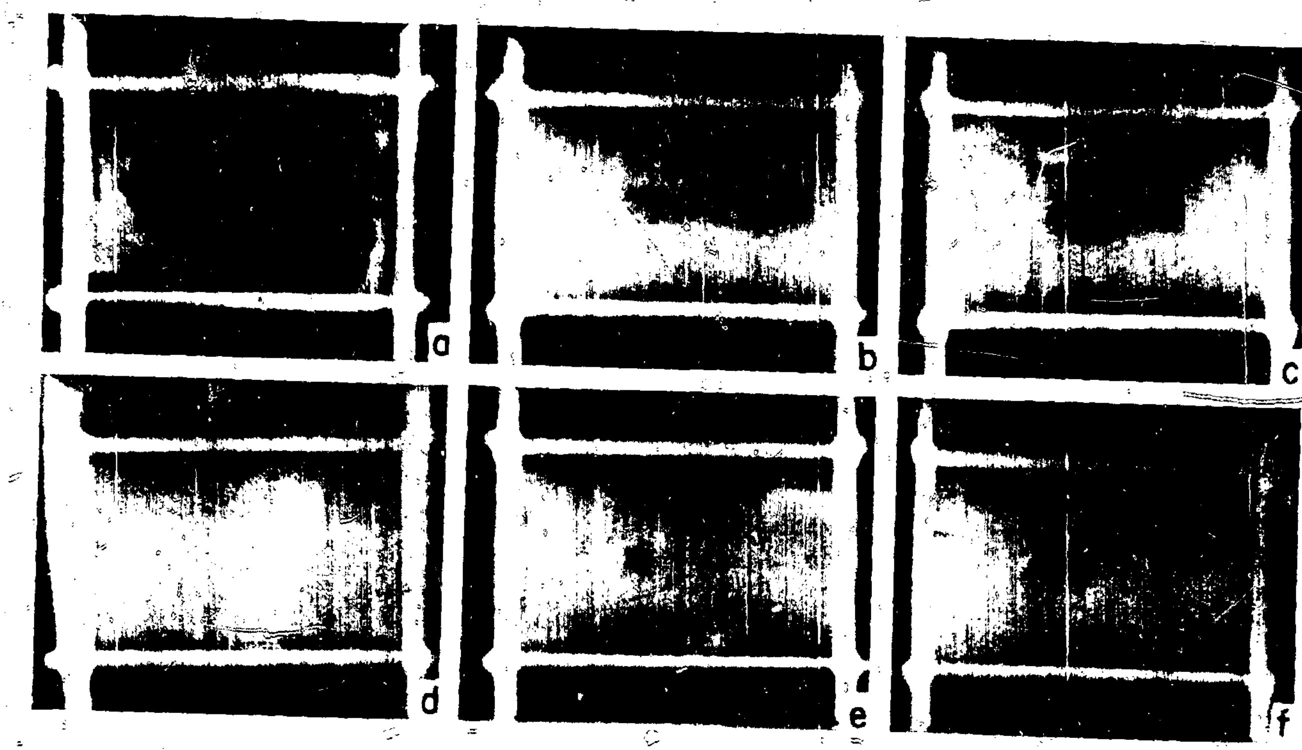

FIGURE 7

MICROSECOND-EXPOSURE X-RAYS OF CONFINED AND UNCONFINED GELATIN CYLINDERS SHOT WITH THE CALIBER .22 HORNET SOFT-NOSE BULLET. A. UNCONFINED CYLINDER, 2000 MICROSECONDS AFTER IMPACT. B-F CONFINED CYLINDERS, 500, 1000, 1500, 2000 AND 2500 MICROSECONDS AFTER IMPACT RESPECTIVELY

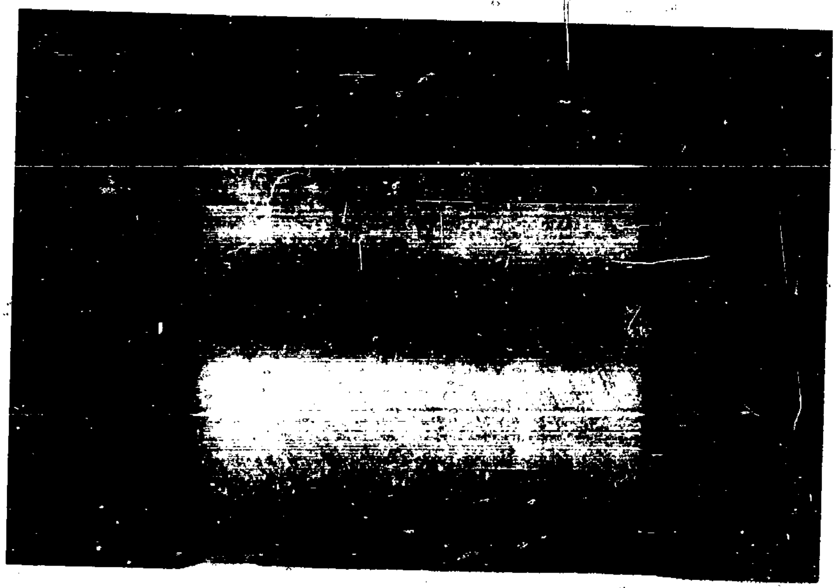

FIGURE 8

MICROSECOND-EXPOSURE X-RAY OF A GELATIN CYLINDER WITH A 1-IN.-DIAMETER HOLE THROUGH THE CENTER, CONFINED WITHIN A 1/4-IN.-THICK PLASTICIZED FIBER-GLASS CASING

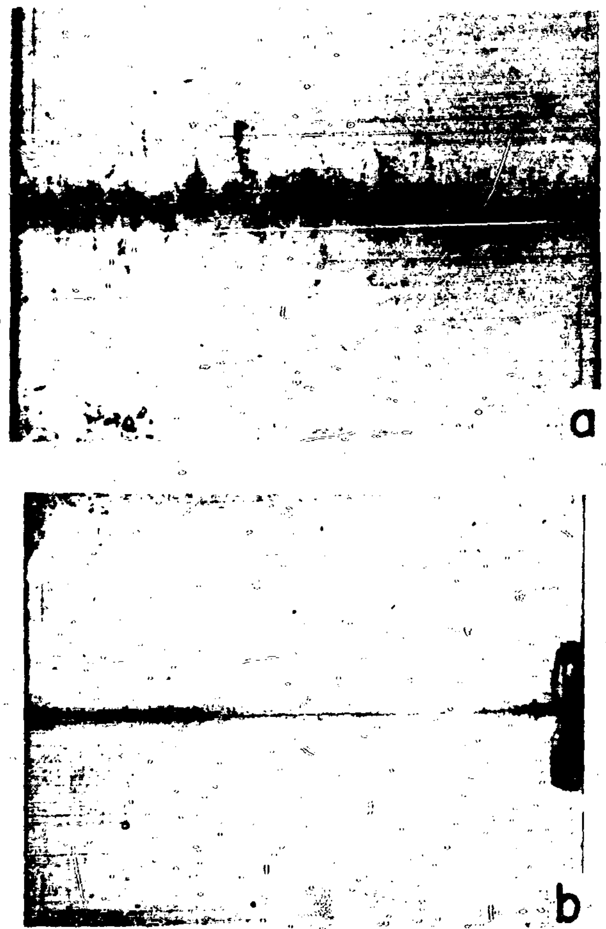

FIGURE 9

PERMANENT TRACTS IN UNCONFINED AND CONFINED 20% GELATIN CYLINDERS MADE BY CALIBER .30 AP M2 BULLETS. A. UNCONFINED CYLINDER. B. CONFINED CYLINDER.

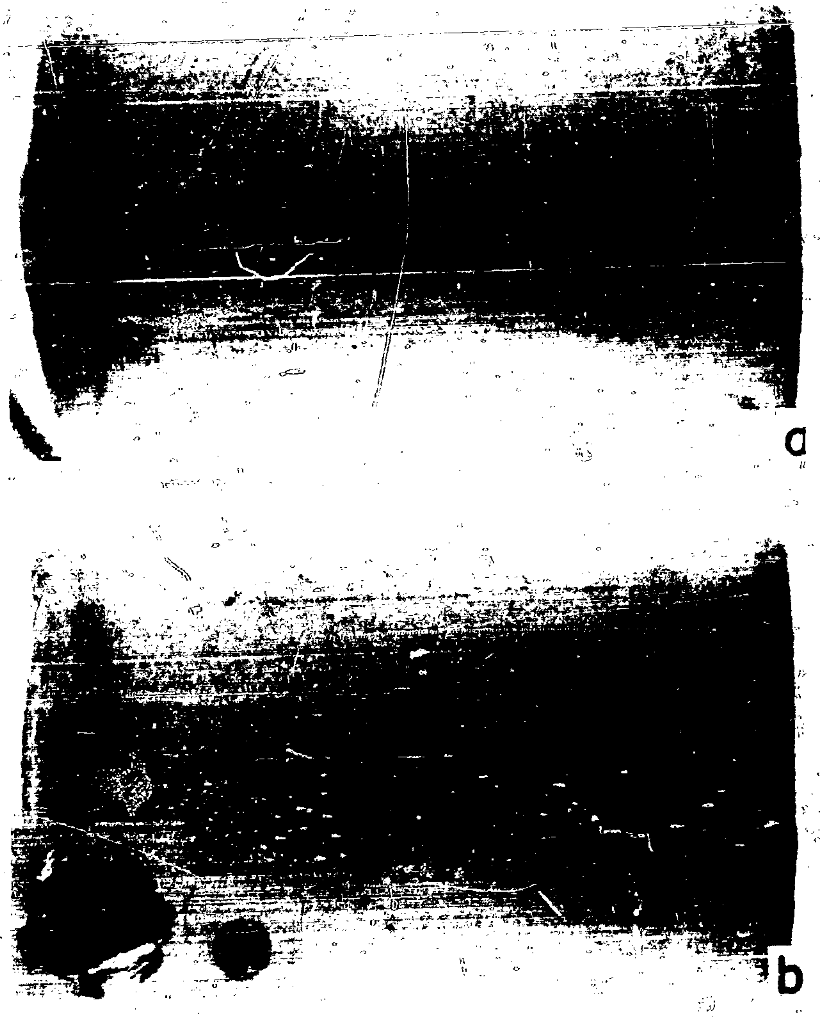

FIGURE 10

PERMANENT TRACTS IN CONFINED AND UNCONFINED CYLINDERS MADE BY CALIBER .22 HORNET SOFT-NOSE BULLETS. NOTE THE DEFORMED BULLET EMBEDDED IN EACH CYLINDER. INSERTS SHOW A MUSHROOMED BULLET RECOVERED FROM A GELATIN CYLINDER IN COMPARISON WITH AN UNDEFORMED BULLET. A. UNCONFINED CYLINDER. B. CONFINED CYLINDER.

From the data shown in table 3, it was found, by applying the t test, that there was no significant difference in the amount of energy absorbed in confined gelatin cylinders and in unconfined cylinders when each was shot with AP M2 bullets ($p > 0.05$). Since, however, AP M2 bullets lose less than 10% of their total kinetic energy in passing through 12.5 cm of 20% gelatin at the velocities employed in these experiments, another series of six confined and an equal number of unconfined gelatin cylinders were shot with 1/4-inch steel spheres. The impact velocity of the spheres was between 2400 and 2500 ft/sec, and at this striking velocity they lost approximately 70% of their initial kinetic energy upon traversing 12.5 cm of 20% gelatin. Again, however, the data as shown in table 3 indicate that there is no significant difference, by t test ($p > 0.05$), between the confined cylinders and the controls with respect to the amount of energy absorbed.

It would appear from these results that the amount of energy transferred from a high-velocity missile to 20% gelatin is independent of constraining forces that may be imposed on the gelatin. In this connection, it should be noted that microsecond X-rays of gelatin blocks shot with the 1/4-inch spheres show that temporary cavity formation is almost completely suppressed in confined cylinders, as in the case of cylinders shot with AP M2 and caliber .22 Hornet bullets.

D. Transfer of Momentum in Confined and Unconfined Gelatin Cylinders.

The fact that energy absorption appears to be independent of external constraining forces imposed on gelatin, and hence is also independent of temporary-cavity formation, raises the question of whether the suppression of a temporary cavity is compensated for by a measurable difference in momentum transfer in confined as compared with unconfined gelatin cylinders.

Preliminary experiments indicated that unambiguous results might best be achieved with a system in which the missile would impart all of its kinetic energy to a gelatin cylinder set up as a ballistic pendulum. Experience with the caliber .22 Hornet soft-nose bullet had shown that, when fired at a velocity of about 2400 ft/sec, it is defeated by 15 cm to 18 cm of 20% gelatin. Defeat of the bullet is the result of mushrooming, which occurs very soon after impact;[6] figure 10b (insert) shows a soft-nose Hornet bullet that was recovered from a gelatin cylinder into which it had been fired. It can be seen, by comparison with the accompanying picture of an undeformed soft-nose Hornet bullet, that mushrooming of the bullet results in a great increase in its presented area. The temporary cavity produced in an unconfined gelatin cylinder by this bullet is very large (figure 7a), and, as

TABLE 3

COMPARISON OF THE AMOUNT OF ENERGY ABSORBED BY CONFINED AND UNCONFINED 20% GELATIN CYLINDERS SHOT WITH CALIBER .30 AP M2 BULLETS AND 1/4-INCH STEEL SPHERES

Confined cylinders						Unconfined cylinders					
Cylinder	Missile	Wt of missile	Impact velocity	Residual velocity	Energy absorbed by cyl	Cylinder	Missile	Wt of missile	Impact velocity	Residual velocity	Energy absorbed by cyl
		lb	ft/sec		ft/lb			lb	ft/sec		ft/lb
1	AP M2	0.023	2749	2657	174.1	1	AP M2	0.023	2779	2699	153.4
2	AP M2	0.023	2803	2707	185.1	2	AP M2	0.023	2771	2688	158.6
3	AP M2	0.023	2771	2672	188.6	3	AP M2	0.023	2757	2665	174.6
4	AP M2	0.023	2795	2679	222.2	4	AP M2	0.023	2796	2716	154.3
5	AP M2	0.023	2744	2651	175.6	5	AP M2	0.023	2788	2678	210.4
6	AP M2	0.023	2787	2696	174.6	6	AP M2	0.023	2759	2663	182.2
7	AP M2	0.023	2761	2681	152.4	7	AP M2	0.023	2778	2694	160.9
8	AP M2	0.023	2768	2674	179.0	8	AP M2	0.023	2791	2681	166.2
9	AP M2	0.023	2797	2713	162.0	9	AP M2	0.023	2772	2685	218.2
10	AP M2	0.023	2795	2687	207.2	10	AP M2	0.023	2815	2702	151.2
11	AP M2	0.023	2753	2636	220.7	11	AP M2	0.023	2774	2695	176.1
12	AP M2	0.023	2803	2678	239.8	12	AP M2	0.023	2780	2688	178.7
13	AP M2	0.023	2784	2667	223.2	13	AP M2	0.023	2763	2669	210.7
14	AP M2	0.023	2768	2678	171.5					Mean:	176.6
15	AP M2	0.023	2728	2630	183.8					Std dev:	20.3
16	AP M2	0.023	2769	2682	166.0						
17	AP M2	0.023	2785	2698	167.0						
18	AP M2	0.023	2804	2672	253.0						
				Mean:	191.4						
				Std dev:	27.9						
1	1/4-in. sphere*	0.0023	2542	1158	163.7	1	1/4-in. sphere*	0.0023	2557	1144	163.5
2		0.0023	2564	1158	188.4	2		0.0023	2596	1291	181.3
3		0.0023	2656	1205	178.2	3		0.0023	2529	1209	167.5
4		0.0023	2564	1060	196.2	4		0.0023	2512	1183	176.8
5		0.0023	2504	1096	182.5	5		0.0023	2575	1121	193.5
6		0.0023	2442	1067	173.7	6		0.0023	2534	1203	179.1
				Mean:	180.5					Mean:	177.0
				Std dev:	7.1					Std dev:	13.0

* Spheres 1/4 in. in diameter for all cylinders in this group.

noted in a preceding section, is almost completely suppressed in confined cylinders (figure 7b-to f).

For the present experiments, long gelatin cylinders (20.3 cm) were used. Because the caliber .22 Hornet soft-nose bullet is extremely accurate at the 10-yard range at which it was used, a 3/4-inch-diameter hole in the front end plate proved large enough to permit unimpeded penetration of the gelatin. The back end plate was not provided with a hole. It seems safe to say that only an insignificant fraction of the bullet energy was dissipated by blowback through the entrance hole in the front plate. In no case was a grossly detectable amount of gelatin lost by backsplash through the entrance hole.

Figure 11 shows how the gelatin-cylinder assembly was suspended by 10-mil piano wire from the ceiling of the room in which firings were held. The fixed points of the suspension were 48 inches apart on the ceiling, and the vertical distance from these points to the center of the entrance hole was 73.5 inches. The assembly swung freely in a longitudinal direction (in the direction of the bullet path), but transverse oscillation was sufficiently damped to be negligible.

Horizontal displacement of the gelatin assembly was recorded on 16-mm moving picture film, exposed at a rate of 64 frames per second. The horizontal amplitude of swing could be directly determined by the use of a Vanguard motion analyzer in conjunction with a fixed scale in each frame of the film. The period of swing was determined by observation at the time of shooting. Since the velocity of a bifilar pendulum at the center of its swing is very nearly

$$d\sqrt{\frac{g}{l}},$$

where d is the horizontal amplitude of swing, l is the radius of the arc of swing, and g is the acceleration of gravity, the velocity of the present system was calculated according to this relation.

From the laws for a simple pendulum of length l,

$$t = 2\pi\sqrt{\frac{l}{g}},$$

where t is time of the period in seconds. Rearranging this expression,

$$\sqrt{\frac{g}{l}} = \frac{2\pi}{t}.$$

Hence, since t was known in the present instance, $\sqrt{\frac{g}{l}}$ could be calculated

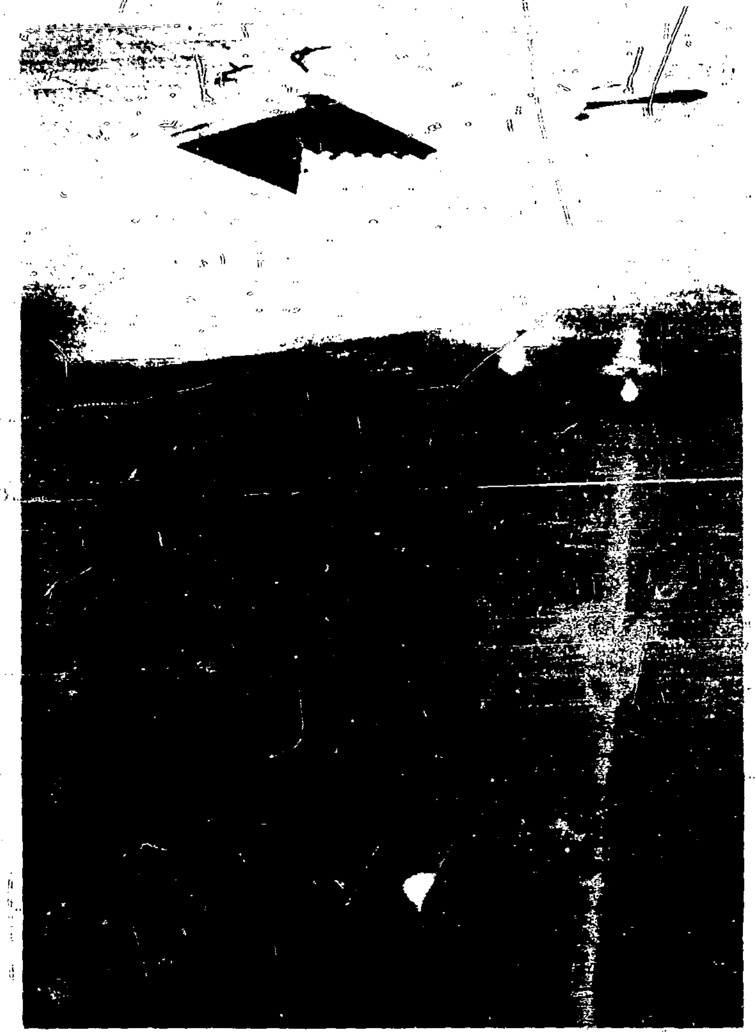

FIGURE 11

SET-UP FOR MOMENTUM EXPERIMENTS

directly. The weight of each gelatin assembly was recorded prior to its being shot, so that the momentum of the system could then be calculated according to the relation

$$M = \frac{w}{g} v,$$

where w is the weight, g the acceleration of gravity, and v the velocity. The weight of the bullet was negligible in comparison with the weight of the cylinder assembly and could be neglected in calculating the momentum of the system.

Initial bullet velocities were recorded and bullet momentum calculated. In addition to determining the momentum of the gelatin assemblies and the bullets, their respective kinetic energies were also calculated according to the relation

$$KE = \frac{1}{2} mv^2.$$

In the case of the gelatin system, v was the displacement velocity. The KE manifested by the gelatin assembly as motion was compared with the total energy absorbed by the system, which was assumed to be equivalent to the kinetic energy of the bullet prior to impact.

In order to eliminate as many variables as possible in the experimental design, a lead sheet was attached to each control (unconfined) system to compensate for the difference in weight because of the casing in the confined cylinder assemblies.

Ten confined and an equal number of unconfined gelatin cylinders were shot. The results are shown in table 4. The momentum acquired by the gelatin systems accounted for from 94% to 98% (mean values) of the momentum lost by the bullets, where the latter is taken as equal to momentum prior to impact, while the kinetic energy of the gelatin systems manifested as motion represents less than 0.1% of the total energy absorbed. The statistical significance of differences between the mean values of the ratios $\frac{\text{cylinder momentum}}{\text{bullet momentum}}$ and $\frac{\text{cylinder KE}}{\text{bullet KE}}$, for the two groups, was assessed by the t test. In neither case were the differences found to be significant ($p > 0.05$).

Implications of the results of these experiments will be considered in the following section.

TABLE 4

COMPARISON OF MOMENTUM AND KINETIC-ENERGY TRANSFER IN CONFINED AND UNCONFINED 20% GELATIN CYLINDERS WITH RESPECT TO THE MOMENTUM AND KINETIC ENERGY OF THE BULLETS

(Caliber .22 Hornet, 45-Grain Soft Nose)

Cyl No.	Momentum of cyl	Momentum lost by bullet	Ratio $\frac{\text{cyl moment}^*}{\text{bul moment}}$	KE of cyl as motion	KE of bullet	Ratio $\frac{\text{cyl KE}}{\text{bul KE}}$
Confined cylinders						
	ft lb/sec			ft lbs		$\times 10^4$
1	.477	.485	.983	.229	588.6	3.89
2	.474	.491	.965	.239	603.2	3.96
3	.471	.493	.955	.232	608.1	3.81
4	.510	.492	1.036	.282	604.7	4.66
5	.483	.494	.977	.238	610.6	3.89
6	.382	.488	.782	.147	595.8	2.46
7	.390	.490	.795	.164	600.7	2.73
8	.451	.497	.907	.205	618.0	3.31
9	.487	.491	.991	.256	603.7	4.24
10	.502	.499	.997	.253	623.5	4.05
Mean:	–	–	.939	–	–	3.70
Std dev:	–	–	.082	–	–	0.71
Unconfined cylinders						
1	.462	.508	.909	.221	644.1	3.43
2	.503	.505	.996	.272	637.6	4.26
3	.502	.501	1.001	.264	627.0	4.21
4	.493	.510	.966	.261	650.8	4.01
5	.502	.496	1.012	.259	614.5	4.21
6	.488	.499	.977	.246	623.0	3.94
7	.493	.499	.987	.249	623.0	3.99
8	.491	.501	.980	.247	627.5	3.93
9	.480	.495	.969	.236	612.6	3.85
10	.502	.507	.990	.259	641.6	4.03
Mean:	–	–	.979	–	–	3.99
Std dev:	–	–	.033	–	–	0.27

* Moment = momentum

IV. DISCUSSION.

Within recent years, microsecond-exposure roentgenographic techniques, combined with high-speed cinematography, have been successfully applied to the problem of assessing the wounding power of high-velocity projectiles.[6, 7] These methods require elaborate equipment and instrumentation, and hence are not available in many situations where accurate evaluation of high-velocity missile effects would be of immediate significance. For example, the surgical problem of debridement of wounds produced by such missiles involves assessment of the extent of tissue damage where there may be no grossly apparent pathological changes.

The extent to which stresses initiated by the explosive radial acceleration of tissues, occasioned by temporary-cavity formation, may be directly responsible for primary irreversible damage to the tissues has recently been at least partially resolved in the case of striated muscle.[8] Secondary effects, probably mainly because of the disruption of the blood supply in the region of a missile wound, are well known to occur at a distance from the permanent cavity. Harvey, et al.,[9] have suggested that the region surrounding the permanent cavity (in which extravasated blood is seen) produced by a high-velocity missile constitutes a region of primary tissue damage. The validity of this assumption has been recently questioned.[10] In any event, the development of valid criteria, by means of which the size (especially the diameter) of the temporary cavity produced by a high-velocity missile in soft tissue can readily be approximated by a surgeon under "field" conditions, is one objective of current investigations.

Studies of wounds produced by high-velocity bullets in isolated soft tissues of goats have shown that there is, at least under controlled conditions, a predictable relation between the cross-sectional diameters, as well as the volume, of the temporary and corresponding permanent cavities.[1] Results obtained in the present investigation with 20% gelatin models provide additional evidence that the diameter of a maximally expanded temporary cavity varies directly with the cross-sectional dimensions of the permanent missile tract. From the data presented in table 1, the relation of the temporary cavity and the longest radial split, representing the cross section of the permanent tract, can be expressed as a ratio. It is of interest that, for the various missiles at the different velocities shown in the table, this ratio varies over a relatively small range of 1.3 to 2.0, with a mean of 1.7, coefficient of variation 11%. In soft tissues (isolated liver and muscle of a goat), the corresponding ratio, calculated from data for wounds produced by stable AP M2 bullets at different velocities, varied from 2.0 to 7.0 (mean values), the coefficient of variation being 13% to 33%.[1] It is not surprising that gelatin

models yield more consistent results, since they are homogeneous in composition and the dimensions of the test cylinders are constant. The results of the gelatin studies provide substantial evidence that the rationale of the tissue-wound investigations cited above is sound.

The present results also suggest that a useful approximation of the dimension of a temporary cavity in 20% gelatin can be achieved without recourse to elaborate instrumentation. As shown here, twice the sum of the length of all of the radiating cracks, at a given level of a permanent tract in gelatin, is closely equivalent to the circumference of the temporary cavity at the same level. By utilizing this simple relation, comparative estimates of missile wounding power, in terms of temporary-cavity dimensions, might be achieved, in at least a preliminary way, in installations in which micronex and high-speed movie equipment are not available.

The phenomenon of temporary-cavity suppression in gelatin cylinders confined within a rigid casing is of considerable interest. It provides strong presumptive evidence that where tissues and organs within the body are subjected to constraining forces, the temporary cavity produced by a high-velocity missile will be modified accordingly. Since all tissues and organs within the body are subjected to constraining forces of variable magnitude, it follows that results of wounding experiments with isolated organs may not be directly applicable to the same organs <u>in situ</u>. This, of course, introduces a complicating factor in the attempt to establish criteria for indirect estimation of the dimensions of the temporary cavity in an organ <u>in situ</u>.

The fact that energy absorption and momentum transfer in 20% gelatin shot with high-velocity missiles are apparently independent of the formation of a temporary cavity suggests that the latter is but an alternative mode of energy dissipation in this system. It has been shown[11] that expansion of a temporary cavity in 20% gelatin is accompanied by an equivalent lateral displacement of the gelatin. If this displacement is prevented by an external constraining force, an internal cavity will not form because 20% gelatin is nearly incompressible. Whether any appreciable degree of solation occurs with the pressures involved has not been determined. It is possible that the absence or near-absence of radial splitting of the gelatin surrounding the permanent tract in a confined block is the result, in part, of a transient solation of the gelatin occurring in this region. It would seem a reasonable assumption that by far the greater part of the energy that would be manifested in formation of a temporary cavity in unconfined gelatin is, in a confined mass, dissipated as heat. The possibility of detecting and measuring this heat, however, seems very slight because of the technical problem involved.

A further point that deserves mention here is the fact that from 94% to 98% of the momentum of the bullet was accounted for by the momentum acquired by the gelatin system acting as a ballistic pendulum. Losses because of friction in the pendulum suspension, blowback through the entrance hole (though loss of gelatin through backsplash appeared to be virtually nil), and bouncing and other oscillations of the system that could not be readily measured probably account for the remaining 2% to 6%.

V. CONCLUSIONS.

1. A useful measure of the cross section of the permanent missile tract in 20% gelatin is afforded by the length of the longest radial split as measured on the surface of the gelatin cylinder.

2. A close approximation to the circumference of a temporary cavity in 20% gelatin is obtained by multiplying by 2 the sum of the length of all the radial splits extending from the missile path at a given level.

3. The formation of a temporary cavity is almost completely suppressed in 20% gelatin confined in a rigid casing. Radial splitting of the gelatin around the permanent missile path is also greatly reduced in confined gelatin cylinders.

4. Energy absorption in 20% gelatin shot with high-velocity missiles is independent of temporary-cavity formation, as shown by experiments with confined and unconfined cylinders.

5. Momentum transfer in 20% gelatin is also independent of temporary-cavity formation.

6. More than 99% of the total energy absorbed by 20% gelatin from a nonperforating high-velocity missile is available for temporary-cavity formation. If the formation of a temporary cavity is suppressed, this energy presumably is dissipated as heat.

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